CHAPTER 14

ELECTRIC MOTORS

14.0 TABLE OF CONTENTS

14.1 INTRODUCTION

Motors convert electrical energy into mechanical energy and play a very important part in supplying power for all types of mechanical equipment such as pumps, compressors and machine tools. They are sometimes classified according to the type of electricity they require including direct current (DC) or alternating current (AC). If AC, the motor may be of a single phase or polyphase design. Electric motors are usually sized in horsepower. The most common sizes are fractional horsepower motors, i.e. 1/2 horsepower or 1/4 horsepower. Larger motors range in size to hundreds of horsepower.

There are many different types of motors to be analyzed for reliability such as the split phase motor, capacitor start motor and squirrel cage motor. The split phase motor is mostly used for "medium starting" applications. It has start and run windings, both are energized when the motor is started. When the motor reaches about 25% of its full load speed, a centrifugal switch disconnects the starter winding. The split phase motor is used where stops and starts are somewhat frequent such as in a refrigerator or air conditioner compressor.

The capacitor start motor has a capacitor in series with a starting winding and provides more than double the starting torque with one third less starting current than the split phase motor. Because of this improved starting ability, the capacitor start motor is used for loads which are hard to start such in a conveyor. The capacitor and starting windings are disconnected from the circuit by an automatic switch when the motor reaches about 75% of its rated full load speed.

A squirrel cage motor includes a rotor with a cylindrical shape containing longitudinal conductive bars usually made of aluminum or copper set into grooves and connected together at both ends by shorting rings forming a cage-like shape. The field windings in the stator set up a rotating magnetic field around the rotor. The relative motion between this field and the rotation of the rotor induces electric current in the conductive bars. In turn these currents lengthwise in the conductors react with the magnetic field of the motor, resulting in torque to turn the shaft. Washing machines and dishwashers are typical applications for the squirrel cage motor.

A gear motor is an assembly composed of an electric motor and a reduction gear in a single unit. A stepper motor converts electrical pulses into specific, rotational movements. Gear motors consisting of an electric motor and a reduction gear train are used in those applications requiring high torque at relatively low shaft speed such as in lifts, winches and garage door openers.

Electric motors are rated as to such variables as voltage, torque, temperature, and speed. Speed is usually specified as RPM at no load condition. As the motor is loaded down, the speed will slow down. If the electric motor is loaded too heavily, the motor shaft will stop. This stall speed should be avoided in any application. This chapter contains failure rate models that apply to all types of electric motors that can be used to support the development of mechanical equipment and provide a reliability estimate for a new motor application, proposed design modification, or an application that is different than specified parameters. The models are intended to focus attention on further design, testing or reliability analysis which should be accomplished to assure the allocated reliability of the motor in its intended operating environment.

14.2 CHARACTERISTICS OF ELECTRIC MOTORS

14.2.1 Types of DC Motors

DC motors consist of armature windings inside another set of field windings called the stator. Applying a voltage to the windings produces a torque in the armature, resulting in motion. DC motors are classified as either series-wound, shunt-wound, or compound-wound. In the series-wound motor the field windings and armature windings are connected in series so that all current that passes through the field windings also passes through the armature windings. The result is a powerful and efficient motor at high speed generating high torque for a given current. Speed will vary with load and can run away under no-load conditions. In the shunt-wound motor, the armature and field are both connected across the main power supply in parallel so that the armature and field currents are separate. Shunt wound motors generate the least torque for a given current but speed is quite constant with load and will not run away under no-load conditions. The compound-wound motor has a combination of series and shunt field windings resulting in a motor that is quite efficient and powerful, yet will not run away under no-load conditions.

14.2.2 Types of Single-Phase AC Motors

Most of the single-phase AC motors are induction motors distinguished by different arrangements for starting. Single-phase motors are used in sizes up to about eight horsepower for heavy starting duty, chiefly in home and commercial appliances for which polyphase power is not available.

The series wound single-phase motor has a rotor winding in series with the stator winding as in the series-wound DC motor. Since this motor may also be operated on direct-current, it is called a "universal motor". The series wound motor has a high starting torque and is used in vacuum cleaners, sewing machines, and portable tools. In the capacitor-start single-phase motor, an auxiliary winding in the stator is connected in series with a capacitor and a centrifugal switch. During the starting and accelerating period the motor operates as a two-phase induction motor. At about two-thirds full-load speed, the auxiliary circuit is disconnected by the switch and the motor then runs as a single phase induction motor.

14.2.3 Types of Polyphase AC Motors

The most extensively used polyphase motors are the induction type such as the squirrel cage induction motor introduced earlier. The wound-rotor type of induction motor has a squirrel cage and a series of coils set into the rotor, which are connected through slip-rings to external variable resistors. By varying the resistance of the wound-rotor circuits, the amount of current flowing in the circuits, and therefore the speed of the motor, can be controlled. Induction motors are manufactured with a wide range of speed and torque characteristics.

The synchronous motor is another type of polyphase AC motor. Unlike the induction motor, the rotor of the synchronous motor is connected to a DC supply which provides a field that rotates in step with the AC field in the stator. The synchronous motor operates at a constant speed throughout its entire load range, after having been brought up to this synchronous speed. This speed is governed by the frequency of the power supply and the number of poles in the rotor.

14.3 ELECTRIC MOTOR FAILURE MODES

A motor is one part of a system that includes its source of voltage, mounting assembly, shaft coupling and driven equipment. The operating environment includes ambient temperature, airborne contamination, shock and vibration. Motor reliability is usually associated with bearing life and the life of the windings before they require rewinding. Bearing failures are normally caused by poor maintenance practices such as allowing contaminates to enter the motor during lubrication, using the wrong grease or oil, and applying too much grease and not allowing the bearing to relieve the excess grease through the drain plug. Loading of the shaft is also a common bearing problem such as incorrect belt tension, dynamic overloading or misalignment. Chapter 7 provides the procedures for evaluating the bearing for reliability.

Another prominent failure mode for a motor is the shorting of the motor winding. Temperature rise is a function of the amount of heat generated in the rotor and stator per unit of time and the efficiency of the heat transfer system. Temperature rise of the windings is critical to motor reliability since insulation materials age over a period of time and this aging process is directly related to temperature. Eventually the materials lose their insulating properties causing a short circuit of the motor. Winding temperatures are related to the power losses of the motor (copper and iron). Copper losses occur as a result of the resistance of the winding and current flow. Iron losses (eddy current losses) are formed in the core of the motor. As these losses increase as a function of time and operation, the winding temperature increases. The permitted temperature rise of the windings is dependent on the class of insulation and temperature limits. Motor overheating is also caused by motor overloading, too high an ambient temperature and incorrect applied voltage. Table 14-2 provides temperature ratings for the various classes of motors.

Excessive frequency of starts and stops of the motor can also contribute to winding temperature rise without allowing the motor to cool between starts. The manufacturer will provide the maximum number of starts and stops per unit time as a function of load and speed. Limiting the frequency of startups per manufacturer's specifications provides adherence to predicted failure rate.

Other modes of motor failure are due to mechanical causes including unbalance, resonance and rotor deflection. The motor shaft is the most common mechanical problem caused by a worn or deformed shaft, incorrect coupling, shaft alignment, and overhung loads. Typical failure modes and their failure causes and effects are listed in Table 14-1. For additional information on individual parts of the motor, the particular chapter for that part should be reviewed as shown below:

1. Bearings (See Chapter 7, Section 7.5)
2. Windings (See Table 14.1 below and Section 14.5)
3. Brushes (See Table 14.1 below)

4. Armature (shaft) (See Chapter 20, Section 20.2)
5. Stator Housing (casing) (See Table 14.1 below)
6. Gears (See Chapter 8, Section 8.3)

Table 14-1. Electric Motor Failure Modes

FAILURE MODE	FAILURE CAUSE	FAILURE EFFECT
- Open winding - Shorted winding	- Insulation breakdown - High ambient temperature - High altitude - Mechanical overload - Frequent stops and starts - Dirt buildup on cooling fins - Vibration - Mechanical shock	- Motor won't start - Motor failure - Sparking at brushes
- Worn bearing: -- spalling --creeping or spin	- Excessive static load - Belt misalignment - Frequent starts and stops under heavy loads - Lubrication problem - Contamination - Overloading or high temperature	- Noisy - Heat build-up - Armature rubbing stator - Motor seized
- Cracked housing	- Fatigue - External shock - Vibration	- Leakage of dust into motor - Shorted or seized
- Sheared armature shaft - Cracked rotor laminations	- Fatigue - Misalignment - Bearing failure	- Seized - Armature rubbing stator
- Worn brushes -- brushes fail open	- Improper maintenance - Contamination - High temperature - Improper contact pressure	- Excessive sparking - Chatter or hissing noise - Motor runs too fast or too slow under load - Motor won't run

Table 14-1. Electric Motor Failure Modes (continued)

FAILURE MODE	FAILURE CAUSE	FAILURE EFFECT
- Noisy operation	- Worn or bent shaft - Shaft alignment - Mechanical vibration - Base plate distortion - Broken motor mounts	- Heat buildup
- Motor overheating	- Frequent starts - Incorrect supply voltage - High ambient temperature - Polyphase voltage unbalance > 1% - Motor overload - Blocked ventilation	- Short motor life - Motor failure
- Overload tripping	- Incorrect supply voltage - Excessive load speed	- Motor won't start
- Bearing failure	- Shaft misalignment - Incorrect coupling - Belt misalignment - Incorrect belt tension - Worn bearing	- Noisy operation - Motor failure

Additional details of failure modes for those components of a motor such as bearings and shafts are included in the applicable chapters of this Handbook.

14.4 MODEL DEVELOPMENT

The failure rate of a motor is affected by such factors as insulation deterioration, wear of sliding parts, bearing deterioration, torque, load size and type, overhung loads, thrust loads and rotational speed. The failure rate model included in this section is based upon identified failure modes of individual parts. The model developed is based on a fractional or integral horsepower AC type motor, although it will be general enough to be applied to most DC and AC motors.

The reliability of an electric motor is dependent upon the reliability of its parts, which may include: bearings, electrical windings, armature/shaft, housing, gears and brushes.

Failure mechanisms resulting in part degradation and failure rate distribution (as a function of time) are considered to be independent in each failure rate model. The total motor system failure rate is the sum of the failure rates of each of the parts in the motor:

$$\lambda_M = (\lambda_{M,B} \bullet C_{SF}) + \lambda_{WI} + \lambda_{BS} + \lambda_{ST} + \lambda_{AS} + \lambda_{BE} + \lambda_{GR} + \lambda_C \qquad \textbf{(14-1)}$$

Where: λ_M = Total failure rate for the motor system, failures/million hours

$\lambda_{M,B}$ = Base failure rate of motor, failures/million hours (See Table 14-3)

C_{SF} = Motor load service factor (See Table 14-4)

λ_{WI} = Failure rate of electric motor windings, failures/million hours (See Section 14.5)

λ_{BS} = Failure rate of brushes, 3.2 failures/million hours/brush (Reference 68)

λ_{ST} = Failure rate of the stator housing, 0.001 failures/million hours (Reference 68)

λ_{AS} = Failure rate of the armature shaft, failures/million hours (See Chapter 20, Section 20.4)

λ_{BE} = Failure rate of bearings, failures/million hours (See Chapter 7)

λ_{GR} = Failure rate of gears, failures/million hours (See Chapter 8)

λ_C = Failure rate of capacitor (if applicable) See MIL-HDBK-217, (Reference 28)

14.5 FAILURE RATE MODEL FOR MOTOR WINDINGS

The life expectancy of a motor winding is primarily dependant on its operating temperature with respect to the permitted temperature rise of the winding. The temperature rise of the winding is a function of the motor design, insulation materials and the operating environment including shaft loading, duty cycle, altitude, and operating temperature. The insulation materials age over time and this aging process is directly related to temperature. Eventually, the materials lose their insulating properties and break down causing one or more short circuits.

Temperature rise occurs in a motor due to the losses that occur in the motor, normally copper and iron losses. The temperature inside the motor will depend on how effectively this heat can be removed by the cooling system of the motor. The difference between the internal and external temperatures is dependent on the thermal gradient and this difference is normally quite low.

The electric motor windings failure rate, λ_{WI}, is derived by Equation (14-2):

$$\lambda_{WI} = \lambda_{WI,B} \bullet C_T \bullet C_V \bullet C_{alt} \quad \textbf{(14-2)}$$

Where: $\lambda_{WI,B}$ = Base failure rate of the electric motor windings, failures/million hours (See Section 14.5.1)

C_T = Multiplying factor which considers the effects of ambient temperature on the base failure rate (See Section 14.5.2 and Figure 14.1)

C_V = Multiplying factor which considers the effects of electrical source voltage variations (See Section 14.5.3 and Figure 14.2 for single phase motors or Figure 14.3 for three phase motors)

C_{alt} = Multiplying factor which considers the effects of operation at high altitudes (See Section 14.5.4 and Figure 14.4)

14.5.1 Base Failure Rate

$\lambda_{WI,B}$ is the base failure rate of the specific motor winding as supplied by the motor manufacturer. The winding will usually be specified in terms of expected life. The base failure rate is then:

$$\lambda_{WI,B} = \frac{1.0 \, x \, 10^6}{L_I} \quad \textbf{(14-3)}$$

Where: $\lambda_{WI,B}$ = Failure rate, failures/million hours

and: L_I = Expected winding life, hours

If a manufacturer's winding life is not available, a winding life of 25,000 hours (failure rate $\lambda_{WI,B}$ = 40.0 failures/million hours) can be expected from most manufacturers (References 28 and 105). The multiplying factors for Equation (14-2) are described in the following paragraphs.

14.5.2 <u>Temperature Multiplying Factor</u>

Temperature is the primary factor that limits the life of motor windings. Heat causes the windings to age and deteriorate, so after time they break down and lose their insulation quality. When this happens, the related electrical components "short" and the motor burns out.

The manufacturer's rating of a motor based on insulation and expected life is provided in 25^{o}C increments. The temperature rating for each class of insulation is defined as the maximum temperature at which the insulation can be operated to yield the rated winding life. The temperature rating for the various classes of insulation is shown in Table 14-2.

Table 14-2. Motor Insulation Ratings

Insulation Class	Temperature Rating *	Assumed Ambient Temperature **	Allowable Temperature Rise	Hot Spot Allowance
A	105^o C	40^o C	60^o C	5^o C
B	130^o C	40^o C	85^o C	5^o C
F	155^o C	40^o C	110^o C	5^o C
H	180^o C	40^o C	135^o C	5^o C

* Maximum operating temperature allowed which includes ambient temperature, allowable temperature rise and a hot spot allowance. Manufacturers may use a mixture of materials in their motors providing a higher allowable temperature than the listed temperature rating for the insulation which permits a higher allowable ambient temperature. Refer to manufacturer's specification if in doubt.

** After adding the ambient temperature + temperature rise + hot spot temperature, any difference between this sum and temperature rating can be applied to ambient temperature

Allowable temperature rise in Table 14-2 is the change in winding temperature from when the motor starts to the final elevated temperature under full load conditions. This temperature is above the ambient temperature around the motor prior to starting the motor. Temperature rise means that the heat produced in the motor windings, friction of the bearings, rotor and stator losses will continue to increase until the heat dissipation equals the heat being generated. A motor is designed so the temperature rise produced within the motor, when delivering its rated horsepower, and added to the industry standard 40°C ambient temperature rating and an allowance for hot spots will not exceed the winding insulation temperature limit for that particular insulation class. There will be hot spots in the winding which are not measured by the normal resistance measurement that measures the mean temperature rise of the winding. Thus, a hot spot allowance is introduced into the difference between the temperature rating and the temperature limit (ambient temperature plus the temperature rise).

Ambient temperature in Table 14-2 above is the temperature of the air surrounding the motor or the room temperature in the vicinity of the motor. The temperature will obviously be higher than room temperature if the motor is operating in an enclosed cabinet. Ambient temperatures in Table 14-2 are assumed values established sufficiently high for most applications so that the following relationship between the temperatures can be used to prevent motor overheating.

Temperature Rating = Ambient Temperature + Temperature Rise + Hot Spot Allowance.

The winding temperature is determined by measuring both the ambient and the hot temperature resistances of the windings. The resistance measurement gives an average temperature which is more representative than spot measurements with a thermometer. This method has become standard because of the dimensional restrictions of so many motor designs, which prevent the use of thermometers. Since temperature measurements provide an average temperature, a standard hot spot temperature is provided in the table to consider hot spots in the winding not detected by the resistance measurements.

The equation for determining the motor winding temperature from resistance readings is as follows:

$$T_{rise} = \frac{R_H - R_C}{R_C}(K + T_C) \tag{14-4}$$

Where:
- T_{rise} = Temperature Rise, °C
- R_H = Hot winding resistance, ohms
- R_C = Cold winding resistance, ohms
- T_C = Cold temperature, °C
- K = 234.5 (a copper temperature coefficient)

Allowing a motor to reach and operate at a temperature 10°C above its maximum temperature rating shown in Table 14-2 will reduce the motor's expected life by 50%

Operating at 10°C above this, the motor's life will be reduced again by 50%. The same relationship exists in reverse if the motor is operated at a temperature 10°C below the rated temperature. For example, if a manufacturer provides a motor with an insulation Class F for a B Class environment, the motor can be expected to last four times as long.

As a result of this relationship between temperature and winding life, a failure rate multiplying factor considering the motor operating temperature is given by:

$$C_T = 2^{(T_O - 40)/10} \qquad \textbf{(14-5)}$$

Where: T_o = Ambient temperature surrounding motor with motor running at expected full load conditions, °C (See notes following)

Note 1 – If the temperature rise of the motor is known as a result of hot and cold resistance measurements T_o can be adjusted accordingly. For example, if the temperature rise of a Class F motor is found to be 100°C as opposed to 110 °C as shown in Table 14-2, this 10 °C differential can be applied to T_o reducing its value by 10 °C.

Note 2 – In determining T_o the installation location of the motor must be considered such as inside an equipment cabinet, next to other operating equipment, etc.

Figure 14.1 shows the effect of temperature on the base failure rate.

14.5.3 Voltage Multiplying Factor

To drive an existing mechanical load connected to the shaft, a motor must draw a fixed amount of power from the source. When the motor is subjected to voltages below the rated value, current must be increased to provide the same amount of power. This increase in current is a problem only if that current exceeds the motor's current rating. When the amperage is above the rated value, heat begins to build up in the motor increasing the probability of motor winding failure.

If the existing mechanical load is light, a decreased supply voltage will create an increase in current in approximately the same proportion as the voltage decrease. This change does not create a problem if the current remains within rated value. However, for a heavy mechanical load, the winding current is already high, possibly causing a voltage that may be lower than that without the load. Thus, any further decrease in voltage increases the probability of a current above rated value and overheating of the motor. Also, the current required to start a motor is much higher than for steady-state operation. Frequent starting as a result of a high operational duty cycle can contribute to an increase in voltage drop and must also be considered in determining the difference between actual and rated source voltage.

When the motor is subjected to a source voltage higher than rated value, the magnetic field of the motor can approach flux density saturation causing the motor to draw more current in an effort to magnetize the iron beyond the saturation point. This increase in amperage creates a corresponding increase in the probability of motor overheating. A failure rate multiplying factor can be established for those situations when the actual voltage is expected to differ from rated voltage:

For single phase motors:

$$C_V = 2^{10\left(V_D/V_R\right)} \tag{14-6}$$

Where V_D = Difference between rated and actual voltage

V_R = Rated voltage

Figure 14.2 shows the effect of voltage differential on the base failure rate.

For three phase motors, the voltage for all three phases must be equaled (balanced) so that the current values will be the same in each phase winding. When the voltages between the three phases are not equaled (unbalanced), the current increases dramatically in the motor windings causing premature motor failure. To determine the voltage unbalance, the average voltage of the three phases (AB, AC, BC) is measured and the average voltage determined. The average voltage is then subtracted from one of the voltages that will indicate the greatest voltage difference. This (greatest voltage difference divided by the average voltage) x 100 provides the percent voltage unbalance.

The industry standard recommends that the maximum voltage unbalance be limited to 1%. A motor should never be operated with a voltage unbalance exceeding 3%. A failure rate multiplying factor for voltage unbalance can be established as follows:

For three phase motors:

$$C_V = 1 + \left(0.40\, V_U\right)^{2.5} \tag{14-7}$$

Where: $V_U = \%\ \text{voltage unbalance} = 100 \text{ x } \dfrac{\text{greatest voltage difference}}{\text{average phase voltage}}$

And: V_U = 0% to 3%

Figure 14.3 shows the effect of voltage unbalance of the base failure rate.

14.5.4 Altitude Multiplying Factor

Motors operating up to and including 3,300 feet can be considered as operating at sea level. Above 3,300 the low density air does not allow a motor to cool as well as the air at sea-level. However, the decrease in ambient temperature characteristic of high altitudes somewhat compensates for the increase in temperature rise due to low air density. The altitude multiplying factor considers the difference between the effect of lower ambient temperature and loss of cooling capability. The following equation provides an altitude multiplying factor.

For operating altitudes > 3300 feet:

$$C_{alt} = 1.00 + 8x10^{-5}\ (a - 3300\ \text{ft}) \qquad \textbf{(14-8)}$$

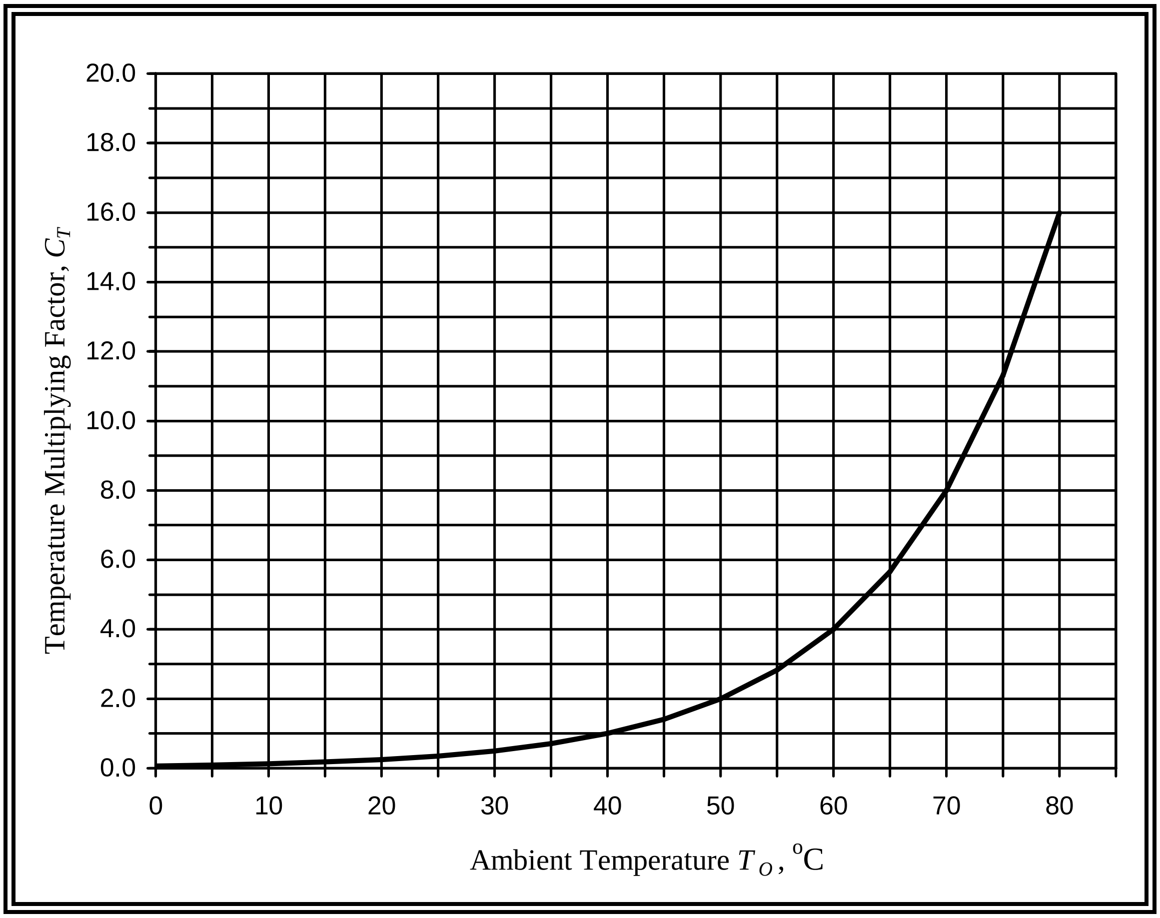
Where a = Operating altitude in feet

For altitudes $\leq$ 3300 ft, $C_{alt} = 1.0$

Figure 14.4 shows the effect of operating altitude on the base failure rate.

14.5.5 Motor Load

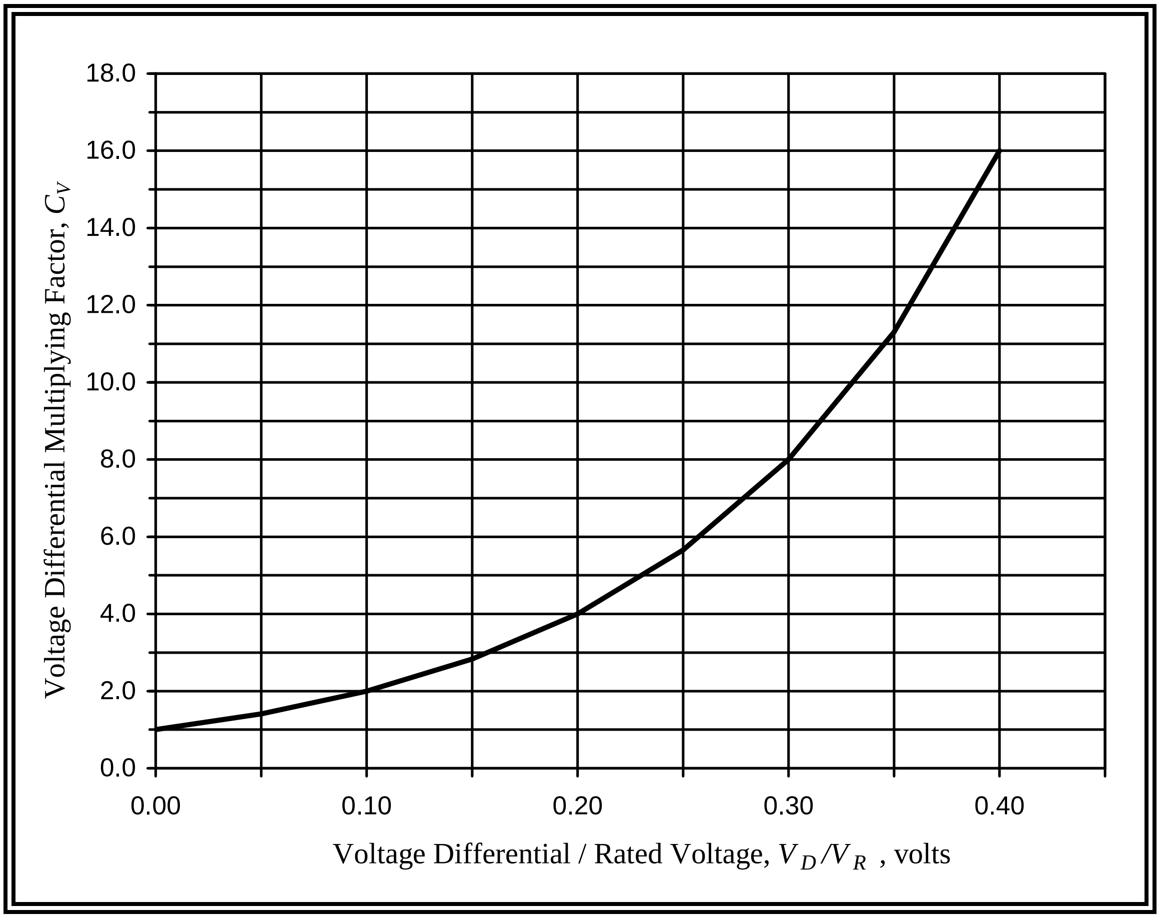
When a motor is operated at full load it has a given temperature rise. Operating the motor at loads above the manufacturer's specifications increases the motor temperature rise and increases the probability of early failure. It is assumed in the motor base failure rate equation that the torque and loading limits of the motor are not exceeded. Table 14-4 provides failure rate multiplying factors for severe loading.



$$C_T = 2^{(T_O - 40)/10}$$

Where: T_o = Ambient temperature surrounding motor with motor running at expected full load conditions (See notes following Equation 14-5)

Figure 14.1 Ambient Temperature Multiplying Factor, C_T

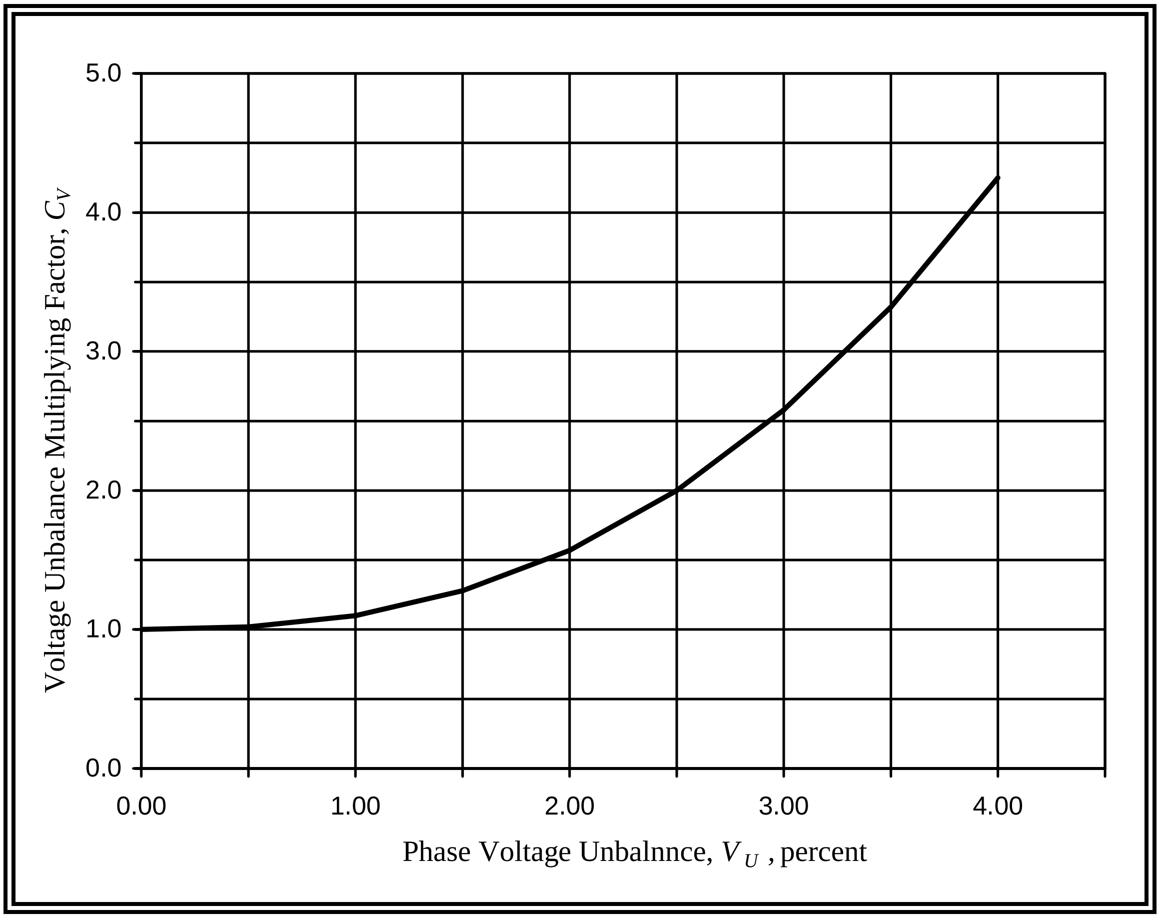


$$C_V = 2^{10\,(V_D/V_R)}$$

Where V_D = Difference between rated and actual voltage

V_R = Rated voltage

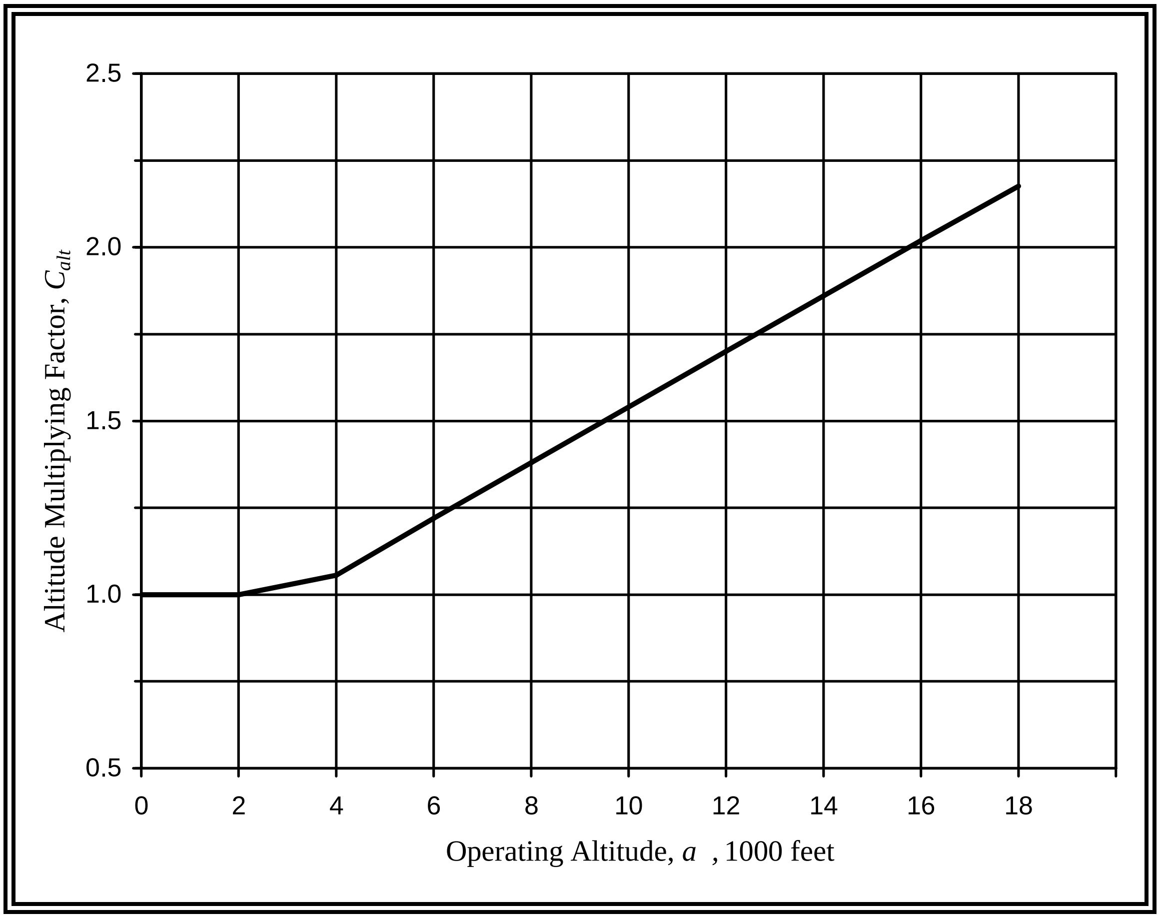
Figure 14.2 Supply Voltage Differential Multiplying Factor



$$C_V = 1 + \left(0.40\, V_U\right)^{2.5}$$

Where: V_U = % voltage unbalance = 100 x $\dfrac{\text{greatest voltage difference}}{\text{average phase voltage}}$

Figure 14.3 Voltage Unbalance Multiplying Factor



$$C_{alt} = 1.00 + 8x10^{-5}\ (a - 3300\ \text{ft})$$

Where a = Operating altitude in feet

Figure 14.4 Altitude Multiplying Factor

Table 14-3 Base Failure Rate of Motor, $\lambda_{M,B}$

Type of Motor	$\lambda_{M,B}$ (failures/million hours)
DC	2.17
DC brushless	1.75
AC single phase	6.90
AC polyphase	10.00

Table 14-4 Motor Load Service Factor, C_{SF}

Load Type	Load Description	C_{SF}
Uniform Load	One way continuous operation, minimal load fluctuation, no shock or vibration	1.00
Light Impact	Frequent starting and stopping, stepping motor operation, minimal shock and vibration	1.50
Medium Impact	Frequent bidirectional, reversible motor operation, moderate load impact ,shock and vibration	2.00
Heavy Impact	Subject to heavy vibration, shock loads, heavy load fluctuations	3.00

14.6 REFERENCES

In addition to specific references cited throughout Chapter 14, other references included below are recommended in support of performing a reliability analysis of electric motors.

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